INTRODUCTION

To survive, humankind needs a healthy and biologically diverse ocean.[i] This can only happen if we have a broad understanding of the ocean environment. Such understanding makes possible management of our interaction with it and sound use of the ocean's resources. The United States will advance basic and applied ocean science research by developing a comprehensive national oceanographic research strategy that establishes ocean research priorities that address pressing national and global issues, capitalizes on existing infrastructure, and identifies future needs.

The ocean is vast and complex, making it a challenge to sample, observe, and model. Ocean processes vary on a wide range of temporal and spatial scales—from seconds to decades, from micrometers to thousands of kilometers—and many processes are linked in ways we have yet to understand.

Our recognition of the complexity of the ocean environment, and our interaction with it, led to significant investment in oceanographic research in the 20th century. In the middle of the century, oceanography benefited from World War II-related scientific and technological initiatives. These programs were followed by major advances during the International Geophysical Year, the International Decade of Ocean Exploration, and the Cold War, and during the growth of satellite observation of the ocean. The result was a greatly improved understanding of the physical, chemical, biological, and geological properties of the global ocean—but also an increased awareness that a more complete understanding of the Earth system, our connection with it, and impacts on it, will come only through studies of the ocean's processes and components, and the exchanges that occur at the ocean's air, land, and seafloor boundaries[ii].

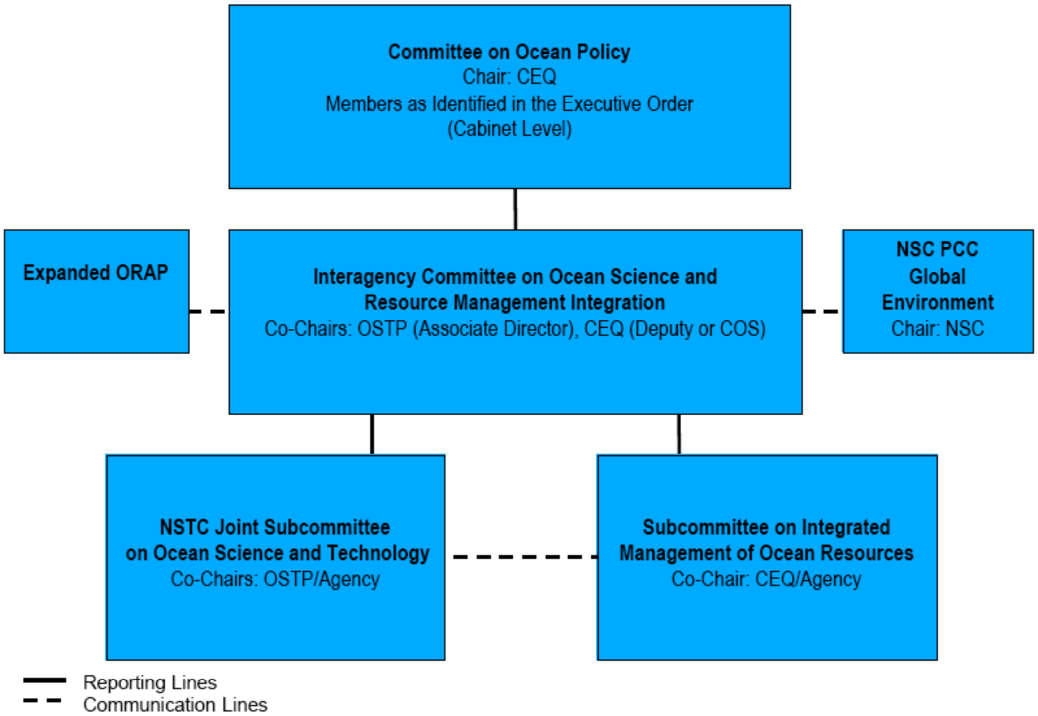
As our nation's scientific and technological oceanographic portfolio has grown, support for oceanographic research has expanded beyond the boundaries of any single funding entity. Ocean-related research now covers a multitude of geographic regions, environmental phenomena, agency mission mandates, and regulatory implications. What started as independent research activities addressing singular issues (e.g., resource deposit distributions, fisheries-stock assessments, ocean-current structure) is expanding into interdisciplinary research on some of today's most pressing global Earth system challenges (climate change, ecosystem management, public health, hazard mitigation). This evolution demands an ocean research plan that maximizes the opportunities to collect, manage, and analyze ocean data; that provides ways to share assets (e.g., personnel, platforms, computational systems); and that ultimately delivers the information required for policy-makers to make informed decisions on the use and protection of the ocean. Central to this effort is identifying and prioritizing oceanographic research objectives that address pressing national and global issues for domestic policy, economic policy, homeland security, and national security.

BACKGROUND TO PLANNING MATERIALS

The U.S. Commission on Ocean Policy was tasked by Congress[iii] to investigate and provide recommendations for a "coordinated and comprehensive national ocean policy." After extensive hearings and written input, the Ocean Commission produced "An Ocean Blueprint" with more than 200 recommendations. Based on the results of the Ocean Commission report the administration developed the U.S. Ocean Action Plan (OAP), a broad plan that proposed a fundamental restructuring of ocean governance, research, and management intended to "engender responsible use and stewardship of ocean and coastal resources for the benefit of all Americans."[iv]

As part of the reformulation of ocean policy, the OAP developed a governance structure that coordinates the tasks and goals of all of the federal agencies involved in ocean science and management. This multi-tiered governance structure has the goal of advancing ocean science and use in an integrated and productive manner (Figure 1). To that end, the Joint Subcommittee on Ocean Science and Technology (JSOST), as directed by the OAP and governed by the Committee on Ocean Policy (COP), the National Science and Technology Council (NSTC), and the Interagency Committee on Ocean Science and Resource Management Integration (ICOSRMI), will develop an Ocean Research Priorities Plan (ORPP). The goal of the ORPP is to formulate the priorities for ocean science and technology initiatives across the wide scope of societal interests. The ORPP will subsequently be complemented by the Ocean Research Priorities Implementation Strategy that will define the fundamental principles for guiding actions and programs in support of the research priorities.

Figure 1 Coordinated Ocean Governance Structure



OCEAN RESEARCH PRIORITIES PLAN

THEMES

The Ocean Commission report provided examples of ocean and coastal science needs, but did not attempt to survey all of ocean research or to identify priorities for future research. The first step in our development of a plan that would identify such priorities was the identification of specific themes that would incorporate the scope of the use, impact, and interaction of the ocean, coasts, and Great Lakes with society. The themes were selected as a result of a review of the OAP and U.S. Ocean Commission report, and subsequent discussions by JSOST agency representatives tasked with the generation of this background material. The themes are:

- Enhancing human health
- Improving ecosystem health
- Sustaining natural resources
- Promoting marine operations
- The ocean’s role in climate change and variability
- Mitigating effects of natural hazards
- Improving quality of life

In addition, several elements cut across all of these themes and were identified as cross-cutting themes. They include:

- ❖ Basic understanding of the ocean
- ❖ Research support through ocean observations and infrastructure
- ❖ Expanded ocean education

FRAMEWORK FOR THE OCEAN RESEARCH PRIORITIES PLAN

A framework for the Ocean Research Priorities Plan was developed by the JSOST and approved by the ICOSRMI in April 2005. This framework established the components of the report and the general nature of the content.[v] The framework is shown in Figure 2.

Figure 2. U.S. Ocean Research Priorities Plan Framework

- Vision
- Challenges
- Principles and Critical Elements
- Themes
- Goals
- Resources
- Evaluating Performance

Central to the ORPP are the specific themes. Building on the framework, initial discussions of each theme were based on the combined efforts of federal agencies involved in ocean science and technology and an *ad hoc* group convened by the National Research Council (NRC). Federal agency representatives familiar with current ocean science and technology – as well as existing capabilities and gaps in ocean observations, education and collaborations – drafted the initial description of each theme. Concurrently, the *ad hoc* NRC group reviewed 87 existing National Research Council reports related to ocean science and technology and provided summaries of recommendations provided by each report, categorized by each theme area. The two efforts were combined ensuring that past community efforts in contributing to ocean science and technology priorities were reviewed for incorporation into the development of the plan. The content of the themes consists of an overall vision, a rationale, key large-scale research challenges necessary to achieve the vision, research needs to address these challenges, technology and infrastructure necessary to pursue these efforts, and expected results, in the context of current programs, investments, and capabilities.

The Subcommittee on Integrated Management of Ocean Resources (SIMOR, a sister committee to JSOST, comprised of Federal agency representatives from those agencies having ocean resource management responsibilities) of the ICOSRMI, SIMOR's Federal-State Task Team (FSTT), the ICOSRMI, and the Ocean Research and Resources Advisory Panel (ORRAP, an advisory group consisting of representatives from academia, industry, non-governmental organizations, and state government) reviewed the initial description of the themes and we have incorporated their comments and suggestions in the current description of the themes.

COMMUNITY INPUT

With the framework (Fig. 1) and the initial description of the themes as planning materials, we now seek input and comment from all relevant communities. This document is intended to serve as a foundation from which to generate discussion and recommend priorities during the both public comment and the workshop. The sections within the themes are examples of both the content and the specificity needed for the Priorities Plan.

These background materials will be announced in the Federal Register for a public comment period of 45 days. Within that 45-day window, a public workshop on April 18-20, 2006 in Denver, Colorado, will provide an opportunity for public dialogue and comment. Through the public comment period and the workshop we invite input and guidance on the themes, as well as recommendations for ocean research priorities.

The ocean science communities will also have the opportunity to comment on the draft Ocean Research Priorities Plan. This draft Plan will be generated using the input and recommendations of the workshop groups and the comments received from the first public comment period. We anticipate this second public comment period, scheduled to run concurrently with the NRC review of the draft Plan (discussed below), will open later this year.

SUBSEQUENT DEVELOPMENT OF THE OCEAN RESEARCH PRIORITIES PLAN

Using the comments solicited from the ocean science community during the public workshop and the public comment period, a draft Ocean Research Priorities Plan will be developed by the JSOST. This draft will also be posted in the Federal Register for public comment. In addition, an *ad hoc* committee selected by the NRC will conduct an independent, interim review of the draft ORPP. Based on public comment and the NRC interim review, a final ORPP will be developed by the JSOST. The *ad hoc* NRC committee will also conduct a final review of the Ocean Research Priorities Plan after the final version has been released.

USE OF THE PLAN

The collaborative and comprehensive efforts of the federal agencies, the National Academies, and the community at large will focus the Ocean Research Priorities Plan to provide the best assessment of the most pressing ocean science and technology issues facing the United States. We believe that this approach will pave the way for:

- Stronger rationale for the development of Federal agency ocean research plans, programs and budgets (both individual and interagency efforts),
- A framework and rationale to inform for non-federal (public and private) investments in ocean research,

- Improved tools for the development of business plans among those private sector entities seeking to develop next-generation ocean-based products and services,
- Greater coordination between resource management communities (including states and regional bodies) and the oceanographic research community, and
- Enhanced identification of expected ocean research-based educational products.

GUIDE FOR REVIEWERS

What do we mean by a priorities plan?

A priorities plan is a document that describes the major ocean challenges facing the nation, gives reasons for their importance, identifies the research needs to meet those challenges, identifies the infrastructural needs of the research, and the expected results of the research. Finally, a priorities plan must identify the highest priority research necessary to make significant progress on the challenges.

What do we mean by research?

The ocean challenges proposed in the planning documents require both applied and basic research. For specific themes we have not distinguished between which portions of the research agenda would be applied and which would be basic.

The planning documents that we have provided suggest challenges that will also require basic science advancement – sometimes in fields directly related to the challenge (e.g. advancements in understanding of marine ecosystems in order to understand living marine resources), and sometimes in theoretical science (e.g. understanding controls and scalability of turbulence in order to improve coupled ocean-climate models).

What do we mean by priorities?

We believe that we will make the most progress by establishing a small number of priorities in each of the theme areas that, if funded, would allow us to make substantial progress. We do not anticipate a rank-ordered list of priorities all of the themes.

How can the ocean communities be involved?

The ocean communities have the opportunity to provide input on the development of the Ocean Research Priorities Plan through two mechanisms – a public comment period (http://ocean.ceq.gov/about/sup_jsost_public_comment.html) and a public workshop (http://ocean.ceq.gov/about/jsost_workshop/welcome.html).

How will your input be used?

Using the recommendations from both the workshop and the public comment period, a draft Ocean Research Priorities Plan will be developed by the JSOST. The draft will be made available for public comment later this year.

THEMES

ENHANCING HUMAN HEALTH

VISION

The ocean holds untapped resources for enhancing human well-being, however, it also contains significant health hazards. Research leading to improved understanding of the means by which health hazards arise and can be managed will lead to fewer illnesses from contaminated shellfish, polluted waters, and harmful algal blooms (HABs). Exploration of new habitats, combined with emerging biochemical and biotechnological techniques, will promote drug discovery and development.

RATIONALE

Consuming contaminated foods from their waters, from direct contact with pathogens in those waters, and even from indirect contact such as breathing fresh salt air that may contain algal toxin aerosols are risks that the ocean, coasts, and Great Lakes present to humans.

- Illnesses from pathogen-containing molluscan shellfish, frequently eaten raw, account for a major portion of seafood-related illnesses. Finfish containing marine toxins are another major source of seafood-related illnesses. These illnesses combined are estimated to be ~ 13,000 to 40,000 per year, leading to some 10 to 20 deaths[vi].
- The huge scale and complexity of the ocean and the incredible diversity and numbers of vertebrate animals suggest that the ocean should be considered a major potential reservoir of pathogen threats to humans.[vii]
- Twenty-eight unusual mortality events for marine mammals in US waters alone have been documented between 1991 and 2004, attributed to factors such as disease, HAB toxins, and human interactions, but the causes of 25% of these events have not been determined. These events may be increasing in frequency and severity, suggesting that health threats may also be increasing in many coastal environments.[viii]
- Major gaps exist in illness reporting and epidemiological knowledge of seafood-caused[ix] human illnesses.[x]
- Risks from anthropogenic contaminants, such as methylmercury[86], petrochemicals [23,71], and other current and emerging contaminants, in water, sediment, and most notably, seafood, continue to be a significant health concern.

Isolating the causes and impacts of these hazards will protect human health and safeguard the quality of the seafood supply.

In addition to possible dangers, the ocean also holds a bounty of potential assets.

Oceanographers have recently discovered new species and even completely new ecological communities with unexpected biochemical systems in the oceans. Processes and products from these discoveries now have practical applications, including:

- Pharmaceuticals (i.e., anti-cancer drugs) and diagnostics (i.e., endotoxin detection)
- Molecular probes (used in biochemical process/disease research)[xi]
- Nutrients

Expanded research into these biochemical niches will increase the pace of discoveries of practical value, both to human health and economic development.

CHALLENGES

Adequate monitoring, data collection and assessment, and development of effective response plans present key challenges to counteracting the damaging effects of naturally occurring harmful marine organisms, pathogens introduced through human activities (e.g., wastewater treatment), and contaminants. Some of these challenges, while not specifically oceanographic in nature, are important to express in the context of the nexus and interdependence between biomedicine and oceanography. These include:

- Understanding the ecology and impacts of known and emerging pathogens[49] (including causes of zoonoses) and contaminants.
- Determining triggers for HABs and pathogen outbreaks, and factors that contribute to sustaining these outbreaks (e.g., global warming, nutrient input).
- Predicting the fate and effects of contaminants and toxins within foods webs, with an emphasis on edible seafood.
- Expanding monitoring and assessment of pathogens, HABs, and contaminants.
- Improving demographics of illnesses from marine food and marine environmental exposure[38].
- Expanding biological and chemical human health threat impact assessments to include socio-economic factors, such as impacts on coastal tourism.

Key efforts to advance drug discovery and development in marine systems are timely assessment and preservation of promising environments combined with effective and coordinated investigations. Specifically:

- Threatened communities – Some communities, such as recently discovered deep Antarctic ecosystems[xii] and deep-sea coral reef systems[xiii] are threatened even as they are being discovered, limiting investigations for drug discovery. More accessible coral reef systems that may yet yield useful biological and biochemical components and information are being threatened by pollution, warming seas, and other factors.
- Harvest limitations – Discovery and use of viable pharmaceuticals may be limited by low natural quantities or ecosystem impacts.
- Collaboration – Effective, collaborative studies involving individuals from diverse disciplines, such as oceanography and medicine, are required when environmentally-based

discoveries are made.

RESEARCH NEEDS

Successful prediction and mitigation of water-borne hazards requires expanding efforts in both ocean-based and human-health research. These include:

- Conducting laboratory assessments of the ecology of harmful algae, including toxicity and pathogenicity, and coordinating these efforts with *in situ* monitoring and experimentation to establish causes and perpetrators of outbreaks.
- Conducting food-web assessments and developing models focusing on bio-accumulation and bio-magnification of contaminants.
- Investigating and modeling cycling (sediment, water column, and atmospheric) and potential exposure mechanisms (e.g., seafood ingestion, recreational activities) of contaminants and pathogens, and incorporating model results into risk assessments.
- Assessing impacts of pathogens, HABs, and contaminants on diverse species and habitats to determine viable sentinels and biosensors that demonstrate cumulative effects and long-term risks.
- Developing rapid tests for sporadically occurring toxins for seafood testing where environmental controls appear insufficient[49].
- Expanding risk assessments of seafood and exposure (e.g., swimming, commercial and subsistence fishing) hazards from harmful alga, pathogens, and contaminants to identify and evaluate mitigation options[49,71].

Success in finding new drugs and materials depends upon the integration of research expertise from oceanographers, biologists, biomaterials engineers, pharmacologists, and the medical community. While many avenues exist for drug discovery, key oceanographic research activities using this combined expertise include:

- Intensive exploration of new habitats combined with discovery and culture of new marine microorganisms.
- Enhancing research on marine bioproduct biosynthesis[50].
- Incorporating genome sequencing, proteomics, and bioinformatics with non-culture-based methods for environmental surveying and screening of uncultured microbes[50].
- Enhancing interdisciplinary education and training for scientists in diverse fields to ensure effective collaborations and discovery potential.

INFRASTRUCTURAL AND TECHNOLOGICAL NEEDS

A system capable of recording comprehensive illness data will require expanded environmental monitoring and infrastructure. Central to this effort is the development of sensors capable of detecting biological and chemical parameters, such as microbial densities, species, and contaminant concentrations. Remote sensing of ecological changes and real-time, high-frequency (temporal and spatial) *in situ* monitoring combined with modeling efforts (statistical-empirical and mechanistic) are necessary to track and predict outbreaks and impacts[38]. Additionally, improved coordination of federal and state data systems is needed for toxic algal bloom monitoring, pathogen source tracking, marine disease surveillance, and medical illness reporting[38], and in the design and development a national database of monitoring and screening methodologies[49].

Transferring live systems and organisms from the environment into the laboratory for culture and additional study presents many technical obstacles. Improvements are needed in at-sea vessel collection systems ranging from traditional samplers and divers to robotic instruments, including use of manned and unmanned submersibles with collection capabilities. These capabilities should be coupled to and shared with shore-based laboratories with dedicated facilities and instrumentation (e.g., gene sequencing) and scientific staff capable of successfully investigating the biology and physiology of the recovered organisms and symbiotic systems.

EXPECTED RESULTS

Human health can be compromised through contaminated seafood impacted by contaminants, pathogens, and HABs and exposure to these threats through recreational activities, and commercial and subsistence fishing. Research to understand and model the dynamics and effects of these risks will serve to protect human health, help mitigate potential effects of these hazards, and help increase public confidence in the safety of their food supplies and coastal areas:

- Indicators of enteric virus hazards in harvest waters and molluscan shellfish will be available.
- Human activities contributing to HAB outbreaks will be identified and controlled through management and technological advancements.
- Sources of current and emerging contaminants toxins contributing to seafood contamination will be determined and mitigation strategies, if needed, implemented.
- The rapid detection of key toxins in finfish will allow for the testing of the most hazardous species entering the U.S. seafood supply from imports and domestic sources as such species and their source waters demand.
- Monitoring of key biological and chemical parameters, combined with rapid environmental assessments and more accurate model predictions, will support decision-makers and the development of effective, coordinated, and tested control and response plans.
- Improvements in illness identification and reporting from the clinic to the health agencies will contribute to a comprehensive system that will allow for rapid and accurate risk assessments and mitigation actions based those assessments.

Expanded exploration, discovery, and assessment of new marine environments will promote increased drug discovery. For example:

- Bio-film formation and prevention research will enable commercially viable alternatives to toxic surface paints for bio-fouling reduction, reducing both ecosystem and human health impacts.

- Biological remediation of oil spills will become feasible.
- Technological advancements in ocean exploration, such as underwater vehicles with greater depth capacities, combined with improved assessment (e.g., genomics) and culturing techniques will allow for more efficient and expansive discovery while preserving intact ecosystems.

IMPROVING ECOSYSTEM HEALTH

VISION

Research into the factors necessary to improve and maintain overall marine ecosystem health will help to ensure the integrity and sustainability of these systems and the continuity of the wide range of goods and services that they contribute to a stable and sustainable biosphere. Comprehensive, well-focused, interdisciplinary research can provide the information needed to allow ocean resource managers to consider the competing uses of the marine environment and to better predict impacts to ecosystems.

RATIONALE

Marine ecosystems are integral to our way of life. They range from deep ocean waters to the Great Lakes, to coastal waters (including bays, estuaries, and wetlands). Marine and Great Lakes ecosystems interface with terrestrial ecosystems not only at shorelines, but also through vast riverine watersheds. These ecosystems contain diverse biological communities structured by complex physical, chemical, and ecological interactions, and they provide abundant products and services that enhance our lives and are essential to maintaining life on Earth. However, these ecosystems are finite and vulnerable to overuse or misuse from the multitude of human activities occurring in the oceans. The goods and services provided by marine and Great Lakes ecosystems include:

- Climate regulation – The oceans are a major reservoir for water, heat, nutrients, and carbon, all of which influence Earth's climate and affect climate variability. Over millions of years, marine photosynthesis has produced a large share of the oxygen we depend on for life.
- Recreation – Tourism is now one of the world's largest economic sectors and the marine environment and its diverse biological communities provide recreational opportunities such as boating, fishing, going to the beach, swimming, diving, bird- and whale-watching, and exploration. In 2002, recreational boating retail expenditures alone exceeded $30 billion.[xiv]
- Waste disposal and pollution control – Coastal and deepwater ecosystems are often the sites of solid and hazardous waste dumping and dredging activities that dilute wastes, but in some cases alter or destroy affected ecological communities.
- Food and marine products – Living marine resources annually produce 80–85 million metric tons of food for human consumption. Marine ecosystems produce a wide range of products that enhance our lives, ranging from medicines for fighting cancer and heart disease to toothpaste and ice cream. These resources will be discussed in the section on Living and Non-living resources.

The array of human activities affecting the marine environment is so complex that decisions are now usually made sector by sector (e.g., recreation impact, waste disposal), with little integration of the cumulative effects of various activities on ecosystems. Advanced understanding of ecosystem function and impacts on ecosystems will enable more comprehensive management and governance of these vital resources. Human activities that are informed by scientific understanding will help ensure the sustained productivity and diversity of marine ecosystems, as well as the social, economic, ecological, and human-health-related benefits we derive from them.

CHALLENGES

Marine ecosystems are molded by their biological, physical, and chemical environments and are linked in intricate and extensive food webs by ecological interactions such as predation, competition, and various forms of symbiosis. Key challenges remain in understanding ecosystems and providing critical information for effective ecosystem-based management:

- Understanding the structure and functioning of marine ecosystems by relating the processes (physical, chemical, biological, geological, ecological) that shape ecosystems and investigating their productivity, diversity, complexity, and intra- and inter-connectedness (between ecosystems and with seafloor, land, cryosphere, and atmospheric processes).
- Characterizing ecosystem status and change (e.g., impacts of climate change and variability) through assessment of properties and processes that lend stability and resilience to ecosystems, as well as the physical and biological forces that drive ecosystem dynamics over various temporal and spatial scales.
- Exploring the marine environment to identify and evaluate ecosystem products and services to enhance human life (e.g., food sources, industrial raw materials), as well as the capacity of these ecosystems to provide such goods and services.
- Determining the individual and cumulative effects of human activities on ecosystem function and biodiversity, including the limits of ecosystem health and stability in the face of growing human use[30] and resource extraction[63].
- Integrating socio-economic activities with marine ecosystem function into management and governance efforts to maintain the health and sustainability of those systems.

RESEARCH NEEDS

Marine ecosystems, by their nature, are multifaceted and complex. The following research efforts will be key to improving our ability to assess, describe, and model ecosystems, including their components and processes[43]:

- Develop measurable indicators of ecosystem status[28] that are consistent with explicit ecosystem goals and objectives, and that can be used to guide research and restoration strategies (e.g., occurrence or severity of harmful algal blooms, proportion of coastal wetlands adversely modified or destroyed, declines in ecosystem productivity or resilience[91]).
- Identify and characterize key ecosystem issues and threats to ecosystem status (e.g., occurrence of regime shifts[78], introduction and cycling of contaminants[23] and excess

nutrients[19], development of dead zones, introduction of invasive species[75]), including the cumulative effects of multiple stressors.

- Identify and understand the role of biodiversity in maintaining ecosystem stability and resilience.
- Establish research efforts that recognize ecosystem complexity and are addressed at the appropriate spatial (e.g., climate change and the consequences for Arctic nations)[59] and temporal scales (e.g., short- and long-term effects of multiple factors on marine ecosystem productivity and diversity, regime shifts)[42, 78].
- Investigate economic and social drivers (e.g., market and non-market resource valuation, land development, water use) that impact ecosystem health in conjunction with natural processes.

INFRASTRUCTURAL AND TECHNOLOGICAL NEEDS

The continued development and implementation of an integrated ocean observing system (IOOS) is a key component for assessing physical, chemical, and ecological properties of marine ecosystems over time, as well as for assessing human impact on key properties including productivity, diversity, and resilience.

Key physical elements of ecosystem observing systems include ships for observing oceanic properties, satellite-based assessment of key surface properties, automated buoys to determine long-term trends in oceanic properties, *in situ* observatories in the ocean and on the seafloor, and a range of survey methods. Plans for deploying these observation systems are in development. Current capabilities can characterize many aspects of the physical, chemical, and geological environment of the oceans. Additional capabilities are needed to gather information about the biological environment, especially below the surface, and thereby provide a more complete understanding of ecosystem status and dynamics[19].

Improvements in information technology and infrastructure also will be essential to ensure that data assimilation, analysis, and modeling tools are available for biological and ecosystem data[91]. Improved capabilities in forecasting, dissemination, and integration of resulting information that will inform management and education strategies at international, federal, state, tribal, and local levels also are necessary[16].

EXPECTED RESULTS

The next decade will give direction to our national marine ecosystem research and management strategy. In this formative period, the goal of maintaining “ecosystem health” will be translated into a framework with explicit, specific, measurable objectives and supported by effective, comprehensive research strategies. Key outcomes of this effort include:

- Identified key ecosystem parameters and meaningful, measurable indicators of marine ecosystem health at appropriate scales. Parameters may include inherent ecosystem properties (e.g., composition and biodiversity, trophic structure, stability, variability, resilience) as well as measures of human impact on them (e.g., status of key indicator communities such as coral reefs; frequency, distribution, and effects of harmful algal blooms and anoxic dead zones; numbers of endangered, threatened, or depleted species in coastal regions).

- A scientific observation and monitoring strategy at the spatial and temporal scales needed to assess the indicators of marine ecosystem health.
- Marine ecosystem and population models capable of assessing and predicting ecosystem dynamics and potential management strategies.
- Methods for integrating marine biological data with physical, chemical, and geological data to investigate the ecological links among them.
- Integrated ecosystem assessment products that synthesize available physical, chemical, geological, biological and human use data for specific time periods and geographic areas.

SUSTAINING NATURAL RESOURCES

VISION

Our management of the diverse use of the ocean's renewable and non-renewable living and non-living resources will be guided by resource and ecosystem assessment and prediction, and will incorporate risk-based management strategies. Improved understanding of the ecological and societal impacts of resource use is central to this vision. Also central is the development of capabilities to predict the effects of multiple controls on resource availability and to more accurately assess the magnitude of resources available for use.

RATIONALE

The resources of our ocean generate tremendous wealth and opportunities. The ocean is a source of food, minerals, pharmaceuticals, and energy, and it is used for transportation, recreation, and tourism.

- The United States has the largest exclusive economic zone (EEZ) of any nation (approximately 4.5 million square nautical miles), not including the coastal areas of the Great Lakes.
- Excluding renewable resources, the annual sales value of oil and gas production on the U.S. EEZ in 2006 is estimated to be about $70 billion. The total market value of the oil and gas inventory is approximately $6 trillion, consisting of one trillion dollars in discovered remaining reserves and $5 trillion in undiscovered technically recoverable resources[xv].
- Fishery production within the EEZ and contiguous inshore waters supports a $60 billion annual seafood industry and a $20 billion recreational industry[xvi]. Aquaculture provides a large and increasing proportion of our seafood supply.
- Healthy ocean and coastal natural resources provide the foundation for a huge coastal tourism industry that is continuing to grow rapidly.
- Over and above their commercial and cultural values, the ocean's systems provide incalculable services, including flood protection (i.e., coastal wetlands), biological production and recycling, carbon sequestration, nitrogen fixation, and neutralization of toxins.

Looking beyond the *currently used resources*, there are emerging opportunities to realize yet greater value from our ocean, such as new energy sources (gas hydrates, wind, wave, current, and tidal), if we develop these opportunities in a manner that is sensitive to their limitations.

CHALLENGES

Aspects of resource use and development sometimes compete with other societal needs and values. For example, increasing domestic energy production from the EEZ (both renewable and non-renewable) is a focal point for enhancing economic and national security, but brings with it concern about environmental impacts. Increasing human population at the coasts and Great Lakes impacts freshwater supplies and, for example, inappropriate wastewater disposal can degrade coastal water quality, impacting living marine resources and human health. A fundamental challenge of resource science and management is effective integration of multiple uses that maintains and, if necessary, rebuilds healthy ecological communities while providing people with the goods and services that they need and expect.

Understanding and predicting how specific activities impact the viability and use of renewable resources is the critical challenge for both the resource scientist and the resource manager. Currently, our ability to assess, and by extension manage, commercial and non-commercial resources is limited by our lack of understanding of the magnitude of those resources and by our lack of understanding of the relationships between the resources and the rest of the marine environment. Improvements are needed to our existing observing systems (e.g., ships, remote-sensing systems, personnel), as well as to our modeling capabilities, including model development and computational resources. Improved understanding and prediction will allow for reliable assessments of individual fisheries, avian resources, and protected species. Opportunities also exist to improve studies of multi-species and ecosystem dynamics (e.g., populations' interactions), combined effects of harvest and other marine, coastal, and Great Lakes uses, and responses to environmental change. Advancing resource understanding and forecasting capabilities will support more effective management of ocean and coastal resources.

The development, management, and use of non-renewable resources must take into account economic and national security issues as well as the potential effects of resource extraction on the natural system. The effective use of other non-living resources (e.g., minerals) requires understanding scientific and economic issues. Balancing environmental impacts of resource use and extraction with the economics of resource development will support more robust and management and governance strategies. For example, preservation of the Flower Garden Banks coral reef system and development of the adjacent oil and gas production area are made possible only through a long-term commitment by all involved parties towards research, monitoring, and mitigation. A critical aspect of any decision-making process in resource management must be supported by research into the human dimension (i.e., economic, social, cultural)[25,72].

RESEARCH NEEDS

Central to effective natural resource management is the capability to accurately and simultaneously determine the effects of multiple drivers on ocean resources and provide a timely assessment of these diverse resources. In addition to expanding research on fundamental ecosystem parameters and processes, as well as the effects of multiple stressors on ecosystems that are discussed in Improving Ecosystem Health, key ocean resource (including coastal and estuarine) research efforts should include:

- Developing capabilities to map the extent and quantity of natural resources (both living and non-living)[18,34] in marine, coastal, estuarine, wetland, and atmospheric (avian) systems, particularly across the EEZ and the delineated limits of the U.S. continental shelf.

- Characterizing habitats of biological resources, both temporally and spatially, to provide both baseline information and to detect changes[29,78].
- Examining the predator-prey and competitive interactions among species, and predicting the impacts of human activities on these interactions and overall community structure.
- Developing more complete and timely information on stock status, with a focus on user-friendly data integration and dissemination formats to enable the transformation of data into useful information supporting management.
- Assessing the quality or capability of resources to ensure maintenance of populations and prevent significant impacts to a specific species or system[14,45,64,78,80]. Concurrent management aimed at recovering depleted populations to their sustainable optima through living resource management activities and technological development to increase efficiency and decrease impact may also be necessary.
- Understanding the cumulative impacts of human activities (e.g., exploration, development, extraction, and enhancements such as aquaculture) on water quality and the ocean's ability to support living marine resources.
- Integrating information on physical dynamics, marine populations (including avian), and human impacts (resource extraction and use as well as indirect impacts from shipping and recreation) into integrated ecosystem assessments, at applicable geographic scales.
- Enhancing modeling and forecasting capabilities, incorporating multiple living and non-living resources and multiple uses.
- Advancing strategies allowing for a transition from non-renewable (e.g., fossil fuels) to renewable energy sources (e.g., wind, waves, current, thermal, tides) while simultaneously assessing their economic and ecological impacts (positive and negative).
- Developing spatial resource evaluation tools for renewable energy to determine effective resource use (e.g., placement of wind or sub-sea turbines), and assess and resolve potential impacts and conflicts.
- Integrating ecological, physical and socio-economic assessments and modeling efforts to evaluate the impacts of alternative use scenarios, which will help support more robust policy frameworks.

While each of these research requirements address critical, national, resource issues, research efforts must also be adapted to address research needs specific to geographic regions. Different geographic regions inherently have diverse natural resources, such as abundant energy sources in the Gulf of Mexico, a significant freshwater supply in the Great Lakes, and large fisheries habitats off the East Coast, and thus various resulting management needs. As a result, focused research efforts will vary with region.

INFRASTRUCTURAL AND TECHNOLOGICAL NEEDS

Technologies and procedures will be needed to enable rapid, efficient, and synoptic assessment of marine resources (and associated physiochemical parameters). . It has been estimated that the national fleet of ships supporting living marine resource assessments is only about one-third of that necessary to provide essential information on the status of managed populations and ecosystem effects of human activities[xvii]. In addition to expanded fleet capacity, improved remote-sensing tools (e.g., satellites, surface current mapping radar) are needed to be able to obtain necessary biological (e.g., migrating birds, schools of fish, pods of dolphins) and physical (e.g., current direction, wave height) parameters. New and improved technologies and protocols will be needed to expand the capabilities of fixed and mobile platforms to include biological and chemical sensors capable of monitoring ecosystems and non-living resources, as well as advanced acoustics to enhance fish surveys.

Enhanced information technology and infrastructure will also be necessary to ensure adequate computer-based data assimilation, analysis, and modeling of collected data[91], and to provide mechanisms for dissemination (e.g., GIS-based decision support tools) and integration of resulting information into our management and education strategies at international, federal, state, tribal, and local levels.

EXPECTED RESULTS

The research outlined here, in conjunction with that outlined in Improving Ecosystem Health, will support an interdisciplinary, multi-faceted system of ocean, coastal, and Great Lakes resource management. This system will combine characterization, monitoring, and modeling, and provide a framework to enable multiple-use decisions in terms of "adaptive management." This approach will ensure a timely feedback between the scientific and the resource management communities and allow for the effective, efficient use of information for both national and region-specific issues.

In the next decade, this approach to informing ocean resource management will provide the basis for long-term policy and planning focused on issues of sustainability, ecosystem health, and quality of life. The expected benefits of such an approach include:

- Assessments of living and non-living marine resources and populations at a resolution necessary to determine their sustainability and/or magnitude and integrated assessments of ecosystems supporting them.
- An understanding of how fishing efforts permanently alter fisheries' population structure
- Higher and more sustainable fishery yields from the US EEZ, including expanded production from offshore aquaculture, improved management of living resources including reduction of overfishing to ensure sustainability, and restoration of fisheries and protected species to their optimal population sizes.
- A narrowing of the time scales in responding to pollution events and to the mitigation of

unplanned environmental impacts.

- Rapid assessment of impacts on ocean resources and related systems, and determination of gaps in necessary information.
- Better use of adaptive research efforts and management protocols.
- The ability to document the effectiveness of these research-monitoring-management strategies through an integrated suite of performance measures simultaneously tracking multiple parameters.
- A better-informed public with the next generation of ocean scientists and resource managers leading an integrative resource management-science approach.

PROMOTING MARINE OPERATIONS

VISION

Marine operations are an essential component of the global economy[xviii] and a critical element of competitiveness and homeland and national security. Coordinated and integrated scientific and technological advances will enable marine operations[xix] to meet challenging requirements for increased levels of transportation efficiency and safety, national security, homeland defense, and preservation of the environment. The critical task for the next ten years is to integrate requirements, advances, research, and operations.

RATIONALE

Efficient, safe, and secure marine operations are vital to the United States. Even a short interruption in the maritime logistics chain has serious consequences for local manufacturing plants, merchandisers, and service industries; a terrorist event or major accident in a key port or waterway would have a significant impact on the nation's economy.

- In 2001, ships carried 78% of U.S. international merchandise by volume[xx,xxi]. Most imported and exported cargo in the United States moves through a widely distributed network of 326 ports (more than six million containers arriving from foreign ports are unloaded in U.S. ports annually)[xxii].
- A strategic scenario of a terrorist event conducted in 2002 demonstrated the potential for $60 billion in losses in the case of a closure of all ports in the nation[xxiii].
- Marine transportation remains an attractive target for terrorists. Over six million containers enter the country every year. 100% of arriving international goods and containers are screened, and high-risk cargo and containers are identified. Research is ongoing to develop new and innovative ways to screen and examine imports vital to the U.S economic strength.[xxiv]

U.S. national and homeland security depends upon a broad set of marine operations in U.S. coastal waters and globally, including:

- Observing and forecasting the marine environment, including ocean and atmosphere[xxv], taking into account the coupled nature of the ocean and atmosphere.
- Efficiently moving ships in the global commons and in national waters for both national security and economic stability[xxvi].
- Protecting marine resources[xxvii] while allowing testing/training of personnel in various scenarios encompassing both military and transportation operations.

CHALLENGES

U.S. trade is projected to triple by 2020; the majority of our commerce (by weight) moves by ocean, hence, the capacity of the U.S. marine transportation system must increase. Many of the marine transportation research concerns also apply to our national and homeland security operations domestically and abroad. National security operations in the ocean take place globally, and often involve persistent monitoring of environmental conditions using new tools such as autonomous sensors, targeted observations, and adaptive modeling. Major efforts to enhance both marine transportation and security include providing:

- Improved gathering, integration, sharing and dissemination of raw and derived data and information products to assure efficient and safe marine transportation and enhanced national and homeland security.
- Improved navigation safety and efficiency (e.g., charts and navigation aids) for all high traffic areas, including operations in ice-filled waters in the Great Lakes.
- Reduced environmental hazard levels, including water and air pollution, management of dredged materials, invasive species, and interactions (including acoustic) with marine life, along with minimized boating impact through improved boat design and hull maintenance.
- Enhanced port and navigation transport system security.
- Improved systems (including atmospheric and oceanographic dispersion modeling[87]) for responding to natural, accidental, and terrorist disruptions, and restoring operations with minimal impact on commerce, national security, and the environment[88].
- Integration of requirements, research, procedures, data, and applications, which underlies the individual challenges for marine transportation and national/homeland security. Only in this way will the needs of the diverse but correlated applications be realized while still providing environmentally sound ways of working.

RESEARCH NEEDS

The breadth of necessary marine operations, such as transportation, portside processes, and multiple facets of national and homeland security, requires a diverse, integrated research portfolio that includes:

- Enhancing environmental characterization and forecasting of all ocean conditions (e.g., estuarine, riverine, coastal, and open-ocean currents; turbidity; surface waves; tides; sea-ice extent; biogeochemical conditions) anywhere in the world. Data will be collected at high resolution[33] and in near real time for multiple applications.
- Researching potential changes in high-latitude transportation routes that may result from climate change.
- Developing non-intrusive technology to detect chemical/biological/nuclear weapons in cargo containers.
- Determining exposure pathways, cycling, and cumulative impacts of pollutants from commercial and recreational vessels (e.g., diesel emissions, anti-fouling paints, petrochemical spills) and developing mitigation strategies.

- Investigating interactions of marine operations with marine life (e.g., boat strikes and vessel-generated noise) and migratory birds and introduction of invasive species (in conjunction with research efforts outlined in Improving Ecosystem Health), particularly in sensitive areas such as the Great Lakes, coastal areas with low tidal exchange, and coral reef systems[63,74].
- Identifying rapid, efficient, and environmentally sustainable dredging and dredged material management processes, and disposal options for concentrated sludge resulting from advanced vessel sewage treatment plants.
- Expanding the incorporation of environmental impact research into the development of commercial and military port and vessel maintenance/operations plans; and
- Improving education and training for operators and users of more complex and automated ship systems operations, including deck, machinery, and shore-side systems management; environmental forecasting systems; coastal operations programs; and data systems to underlie marine operations[73].

INFRASTRUCTURAL AND TECHNOLOGICAL NEEDS

Major infrastructure and technology needs are (1) refining and integrating existing research into operational systems (e.g., systems providing real-time navigation data to vessels); (2) advancing sensor and technology development (especially for autonomous[13] and persistent observations[xxviii]) for real-time navigational and security monitoring, tracking and communication, and cargo handling; (3) developing automated and autonomous bottom mapping capabilities for change detection to improve rapid, full-scale survey scheduling[4]; and (4) creating methodologies to address critical gaps in the collection and sharing of information needed to improve safety, environmental protection, and national security[33,58]. A specific example of a potential system that enhances both maritime transportation and homeland security is the shortwave-radio-based mapping of surface currents and waves in our EEZ; a system like this can also contribute to tracking ships and provide the information needed to mitigate oil spills.

EXPECTED RESULTS

Research efforts to support marine operations are essential to maintaining the effectiveness, efficiency, and safety of these vital activities. Expected outcomes from improved basic understanding, science, and implementation[xxix] in the areas of effort identified above will result in:

- Improved navigational aids and services including charts for vessel operations that will significantly reduce operational risks especially in environmentally sensitive areas; the goal is automated real-time updates of electronic charts for bathymetry and surface currents using all available information including on-board and off-board sensors.
- Comprehensive awareness of the maritime environment gained from expanded gathering, sharing, and coordination of information, resulting in significantly increased security

protection, products for higher efficiency and safety of operations, and improved environmental protection; the goal is an optimized fusion of multi-sensor data and predictive numerical models to give nowcasts and forecasts for all information needed, specifically including all ships in the operating domain and their tracks and purposes, and all environmental parameters.

- More intelligent, efficient, persistent, and reliable ocean observing and marine operations resulting in significantly higher levels of risk-reduced operations in the marine, coastal and Great Lakes environments; the goals is to enable autonomous monitoring of parameters in any location, for at least six months unattended.

THE OCEAN'S ROLE IN CLIMATE VARIABILITY AND CHANGE

VISION

The ocean plays a fundamental role in governing climate through its capacity to store and distribute heat and carbon dioxide. For the 21st century, the challenge is to expand our understanding of the ocean's role in climate to increase our ability to predict climate change. Society's ability to respond to climate-related hazards (including extreme events) and climate variability in order to mitigate calamitous losses to life and property as well as to govern policy depends, in part, on our ability to monitor ocean characteristics over its full depth over a significant fraction of the global ocean, and our ability to utilize these data to improve Earth system models and their application to predict future conditions. The growing body of knowledge about the impact of climate on marine chemistry and ecosystems will also enhance ecosystem-based management of the oceans.

RATIONALE

The ocean covers more than 70% of the planet and has a much higher capacity to store heat and carbon dioxide than the atmosphere. Imbalances of the planetary energy budget are manifested in rising ocean temperatures. Because water expands with rising temperature, a warmer ocean leads to rising sea levels, as does runoff from melting of major ice sheets and glaciers. The choice of human populations to live in low-lying coastal regions combined with rising sea and lake level makes it critical to have a more complete understanding of the rate of sea-level change.

The ocean is an important influence on the path and intensity of major storm systems, such as hurricanes, mid-latitude winter storms, and intraseasonal atmospheric oscillations (30–60 day waves, which span the tropical belt and influence monsoon rainfall patterns). Improved predictability of these features will enhance society's ability to prepare and adapt cities and other public infrastructure for the inevitable arrival of a severe event.

The tropical ocean is a vital component of seasonal-to-interannual climate variability. For example, El Niño events are known to have a substantial economic impact on many regions of the world. Long-term (decadal or longer), basin-scale modes of variability are found to have profound influences on local climates and ecosystems, and may influence long wet or dry spells over major continental areas. The ocean is also known to be an important component of the global water cycle - it receives and redistributes freshwater from rivers, continental and ice runoff, and precipitation; and it provides moisture (through evaporation) to the atmosphere that enhances precipitation over the oceans and continents. Large-scale ocean circulation is an important ocean feature with regards to both long-term and possible abrupt changes in climate.

Recently, major ocean regime shifts have been demonstrated to affect marine ecosystems, such as large swings in the populations of major commercial fisheries. The future balance of greenhouse gases in the atmosphere, specifically carbon dioxide (CO_2), will depend on the ocean's uptake of these gases (in both open ocean and coastal systems [e.g., wetlands]). Substantial changes in ocean chemistry as a result of oceanic uptake of these gases may further influence ecosystems. The overall relationship among ocean productivity, climate, and changing ocean chemistry remains poorly understood.

CHALLENGES

Consistent with the scientific challenges identified in the U.S. Climate Change Science Plan[xxx], improving understanding of the ocean's role in climate is critical. The continuing challenge for climate-related ocean research remains the establishment of an integrated system of global ocean observatories (based on quantitative design studies) consisting of:

- A robust ocean observing system capable of standard and sustained observations.
- Integrated data management and communication systems to provide open access, searchable content, and routine delivery to all users.
- Computer models that effectively assimilate information from the ocean observing system and couple to atmosphere, ice, and land models, and can eventually be integrated with ecosystem and other models to provide valuable products and prognostic capabilities.

Despite substantial progress in the 20th century, the technology and vision for this global ocean observing system has only recently been put forward to provide adequate information (initial and boundary conditions) for predicting climate variability and change. By some estimates, half of a rudimentary global ocean observing system has been implemented. Space-based and *in situ* ocean components of this system require substantial further development.

In addition to the establishment of a global observing system, our understanding of the interaction of the ocean with the climate system must be expanded in several key areas:

- Regions
  - Global tropical oceans – Improved understanding of global tropical oceans continues to be of paramount importance in improving short-term climate predictions.
  - Polar regions: We must improve our knowledge of the polar seas and ocean-ice interactions. Currently, the impact of the dramatic lessening of sea ice in the Arctic Ocean is unknown, but likely very important due to the resulting changes in polar albedo and ocean-atmosphere heat exchanges. Additionally, the Southern Ocean is a region of tremendous carbon dioxide uptake by the ocean and significant forcing of large-scale ocean circulation.
- Processes
  - Large-scale, long-term coherent variability - Expanded forecasting capabilities of tropical ocean-atmospheric variability such as El Niño, and the Pacific Decadal

Oscillation, and the North Atlantic Oscillation are necessary to improve short-term climate predictions over the land and ocean[26].

- Large-scale non-linear behavior – Events such as abrupt changes in the large-scale ocean circulation, which are apparent in the historical record, can lead to large and rapid shifts in climate conditions. The theory and record of such phenomena need to be improved to refine long-term projections and assessments of the risk of future abrupt changes[7].
- Ocean variability and interactions – Better observation and understanding of ocean variability needs to be expanded to assess climate impacts and feedbacks on the ocean[20,66,90].
- Mesoscale eddies – Their role in regulating the large-scale ocean response to forcing changes or of their role in establishing the mean state of the ocean is still poorly modeled, despite their ubiquity and energetics.
- Manifestation of ocean-climate change on coastal and estuarine scales – These regional scales are where ocean changes are likely to be noticed first and have direct impact on people and ecosystems.
- Ocean-atmospheric exchanges (fluxes) of momentum, heat, freshwater, and biogeochemical constituents - The lower atmosphere and upper ocean regularly interact and exchange important quantities that help define uptake and redistribution of these variables by the ocean, govern influence of the ocean on the atmosphere, and impact ocean circulations.
- Ocean ecosystems – Increased storage of carbon dioxide in the ocean, along with rising ocean temperature and sea level, have been demonstrated to have potential, but still undefined, changes in ocean ecological processes.

RESEARCH NEEDS

Key research in the next decade will be focused on expanding and enhancing the global view of the ocean's role in climate.

- Enhance research concerning critical processes and coherent large-scale modes of ocean-atmosphere variability.
- Improve knowledge of the polar seas and ocean-ice interactions through those activities associated with the past and current International Polar Years, and through continuing activities.
- Improve understanding of deep-water formation, its sensitivity to climate change, and its representation in coupled ocean-atmosphere models.
- Integrate research on ocean physical, chemical, biological, and ecological processes, and air-sea interactions into ocean models to advance prediction of critical ocean-climate features, including carbon cycling and the impacts of, and feedbacks to, climate changes (sea-level

rise, increases in greenhouse gasses) on ecosystems.

- Improve global ocean-model resolution to resolve the important dynamical scales (down to a few kilometers at high latitude) associated with mesoscale eddies, boundary and equatorial currents and exchanges between basins.
- Assemble analyses of historical data to provide a consistent picture of the role of the ocean in climate variability and change. These analyses will need ocean models as well as data assimilation frameworks to understand the global state of the ocean, especially for initializing coupled climate predictive models.
- Develop a tropical ocean observing system to facilitate improved intraseasonal to interannual climate predictions. Complete the global ocean observing system, and include the capability to measure and monitor the large-scale ocean circulation, including the western boundary currents. Finally, continue critical satellite observational capabilities to provide global information on key variables such as ocean surface topography, ocean vector winds, chlorophyll, sea-ice extent, and SST.
- Implement coastal observing systems (based on quantitative design studies) and integrate these systems into the global observing system. This integration will help advance understanding of the impacts of climate on coastal and marine ecosystems and landforms. Spatial and temporal sampling requirements vary greatly depending on location and parameter.

INFRASTRUCTURAL AND TECHNOLOGICAL NEEDS

The growing ability to deploy a sustainable global ocean observing system for climate studies has been a major achievement of the past two decades. Implementing, maintaining, integrating, improving, and evolving the system will be priorities for the next decade[8,20,26,90]. The development of an integrated coastal and global ocean observing system will permit an improved understanding of land-ocean-atmosphere interactions, which is especially important for determining the carbon budget and nutrient loading. Passive and active autonomous vehicles with two-way communication systems will provide an ability to monitor boundary currents and their transports, as well as coastal processes for the first time. A major research frontier will be improved satellite and *in situ* ocean sensors that collect information on a broader range of climate parameters, such as currents, salinity, and sea-ice thickness. Next-generation *in situ* chemical and biological sensors that collect a variety of information, including data on sentinel organisms and habitats, will also be important. This enhanced data collection must be accomplished while maintaining long-term climate records of key variables such as ocean surface topography, ocean vector winds, chlorophyll *a*, sea-ice extent, and sea surface temperature.

An integrated delivery system for global ocean observations needs to be constructed to provide open access and routine delivery to all users[3]. In addition to expanded systems capable of incorporating[21,67] and managing large volumes of observational data, ocean and coupled climate model[46] improvements will be necessary to assimilate data into a physically consistent format. Significant computational capability, including versatile software, efficient algorithms, focused resolution, and capacity will be required to support these advances in data and modeling capabilities.

EXPECTED RESULTS

Expanded research into potential drivers (e.g., sea-ice reduction), processes, and feedbacks (e.g., ocean-atmosphere coupling) will promote more comprehensive understanding of the ocean's role in climate variability and change. The ability to monitor and model the ocean, as part of the coupled ocean-climate system, will provide breakthroughs in understanding and improved prediction of major climate events and diffuse some of their negative impacts on society through early warning and adaptation.

- Improved projections of the changes in the intensity and frequency of hurricanes as a result of the ocean's role in climate variability and change will assist in advancing precautionary measures.
- Advances in intraseasonal to interannual climate predictions (e.g., El Niño events) will allow greater lead time for adaptation measures to be implemented and negative economic impacts limited.
- Breakthroughs in decadal-centennial climate projection will allow for improved planning of societal infrastructures (e.g., predicting future rise in sea level can be used for the planning of future coastal infrastructure).
- Documentation of the ocean's role in carbon uptake and its impact will advance global carbon budget modeling and inform policy considerations related to CO_2 emissions.
- Understanding climate impacts on marine ecosystems, including coastal and estuarine habitats, and advances in ecosystem forecasting will enhance ecosystem-based management of limited marine living resources, including fisheries, corals, and protected species.
- Accurate representations of fundamental ocean-climate processes in ocean models will improve predictions of the probability of abrupt ocean regime shifts, including interior ocean ventilation patterns and changes in large-scale ocean circulation.
- Improved model simulations and access will enhance the utility of model predictions as decision support tools.

MITIGATING EFFECTS OF NATURAL HAZARDS

VISION

We cannot eliminate natural hazards. We can, however, minimize and reduce the impacts of hazards with a persistent and coordinated investment in research and technology. The knowledge and information base developed through these efforts will lead to reduced exposure, lives and property saved, more rapid recovery through strategic policies and planning, effective mitigation, and an informed and effective response.

RATIONALE

With over 50% of the U.S. population living in coastal counties, and that number rising each year, it is critical that the United States be adequately prepared for coastal disasters. Coastal disasters have economic, social, and public-health impacts that reverberate on regional and national scales by disrupting commerce and destroying public and private infrastructure. As we continue to direct significant federal funding on science and technology to assist in reducing the impacts of natural hazards, the United States still faces enormous losses each year from marine and coastal hazards:

- Severe storms, hurricanes, and tornados, and the associated coastal and offshore wind, wave, and current damage – In 2005, Hurricane Katrina devastated the Gulf Coast and is estimated to be the costliest natural disaster yet to strike the United States[xxxi].
- Coastal inundation and flooding from storms, tsunamis, and regional meteorological events – Nationwide, floods were the number one natural disaster in the 20th century in terms of lives lost and property damage[xxxii].
- Earthquakes, landslides, and slope failures along the coast and offshore and resulting tsunamis – On December 26, 2004, an earthquake off the coast of Sumatra triggered a tsunami that produced rapidly moving waves over 100 feet high[xxxiii]. Nearly 300,000 people were killed and more than 1 million displaced[xxxiv].

The costs of these events are substantial and will likely increase. In 2002, insured losses from tropical storms alone totaled over $22 billion, affecting nearly 2.5 million individuals. In http://www.ngdc.noaa.gov/seg/hazard/tsevsrch_idb.shtml demonstrated by the Indian Ocean tsunami, the potential short-term and long-term human and economic costs to at-risk regions (Pacific Northwest, Alaska, Hawaii, southeastern United States, Caribbean) are substantial. A sound scientific and technological basis for decision-making, including improved models of hazard impacts and more accurate and timely forecasts, will support cost-effective strategies. These strategies include those that increase resistance, enhance resilience, or help promote avoidance (e.g., “smart growth”) as indicated by comprehensive assessments of future risk.

CHALLENGES

In 2005 alone, the world witnessed the widespread devastation incurred by multiple types of natural hazards. To cope with these ever-present threats, communities should focus on increasing disaster resilience instead of focusing solely on response and recovery[xxxv] . Key challenges in this effort include:

- Efficient collection, standardization, and dissemination of hazards information (i.e., prediction of events, assessments of risk, potential impacts).
- Understanding short-term (coastal flooding and storm surge, winds, waves) and long-term (changes in storm frequency, sea- and lake-level rise, and coastal erosion) processes and impacts on changing risk and vulnerability.
- Integration of both social (land use, population growth) and environmental (meteorologic, climatologic, oceanographic, geologic) processes to improve forecasts and assessments.
- Development of hazard-mitigation plans and technologies for at-risk communities and marine operations.
- Development of strategies to protect critical infrastructure during and after hazard events.
- Evaluation of community resilience and resistance through the combined efforts of federal agencies, universities, local governments, and the private sector[38].
- Effective hazard education and warning systems.

RESEARCH NEEDS

A strategic framework for all-hazards science and technology priorities and investments will be needed and should include the following research-dependent components:

- Develop an all-hazards information resource – Enhance coastal and marine observing capabilities, including collecting data critical for hazards and vulnerability assessment and modeling[38], such as current and integrated elevation data (high-resolution topographic/shallow bathymetric).
- Enhance hazard understanding – Develop and improve assessments, forecast models, and visualization techniques to provide timely and accurate information on the occurrence and consequences of hazard events[44], including probabilistic models for assessment of the likelihood and impacts of future hazard events over a continuum of geographic scales. Specifically, increase investment in modeling of hazard processes, coastal and seafloor response, wave-height during severe storms, and surge- and coastal-inundation forecasts.
- Develop mitigation technologies and strategies – Create effective and affordable systems, materials, and technologies for hazard-resilient infrastructure. Provide models and assessments of the efficacy of natural (e.g., wetlands, reefs, barrier islands) and engineered systems for mitigation of hazard impacts and risk reduction.
- Protect critical infrastructure systems – Establish integrated risk assessments and models to

develop design criteria for resilient infrastructure, marine operations systems, and critical services continuity.

- Assess disaster resilience – Develop risk and vulnerability assessments for coastal communities and marine operations and economic models for consequence and resilience. Develop, monitor, and evaluate impacts of cost- and performance-effective mitigation techniques. Integrate model and assessment results into emergency and development planning efforts.
- Promote “risk-wise” behavior – Develop a standardized messaging system that is researched, designed, implemented, and combined with public education efforts so individuals understand and respond to hazard warnings[42] with appropriate actions.

INFRASTRUCTURAL AND TECHNOLOGICAL NEEDS

Meeting the broad requirements to reduce hazard impacts and increase hazard resilience will require continued expansion of existing observational systems, data-delivery systems, and modeling capabilities, locally (United States) and globally. Sustained marine and coastal observations, including technological improvements in remote and *in situ* sensing of multiple parameters (oceanographic, geophysical, hydrological, chemical, biological, geographic) are required. Both sustained and rapid deployment modes of operation will be required to provide both baseline (pre-impact) and post-hazard data, ensuring adequate evaluation of potential and realized hazard impacts. A priority is to develop pre-impact deployments that address diverse hazard processes and impacts. These deployments would support integrated development of improved models of, for example, storm evolution and coastal response. increased computational resources and the establishment of community computational standards will support data assimilation systems, coupled Earth/ocean/atmospheric models, and data management and delivery systems. The design and implementation of robust, reliable, and widely available notification systems will promote effective communication of warnings.

EXPECTED RESULTS

In the next decade, natural-hazards research and applications will provide the scientific basis for long-term policy and planning to increase disaster resilience and reduce exposure, and for improved short-term forecasts to support effective pre- and post-hazard response. Research investments, which include sustained and accurate observations, up-to-date characterization of vulnerable environments, assessments of at-risk populations and infrastructure, improved assessments of hazard risk, forecasts of hazard occurrence and impacts, and accurate models and forecasts of hazard processes and impacts, will contribute to the following expected benefits:

- Most of the U.S. coast will have the capability to conduct risk and vulnerability assessments, ultimately contributing to coastal communities having increased resilience to natural hazards[xxxvi].

- Risk and vulnerability assessments will be based on coordinated federal efforts to develop and maintain the necessary geospatial framework and characterization of social and environmental conditions and change.
- Through development and application of regional observing systems, forecast models, and decision-support tools, several at-risk geographic regions will have substantially increased observing and modeling capacity to anticipate and mitigate natural hazards related to storms, including storm surge, coastal flooding, and wind damage.
- State, local, and federal emergency managers will have access to a robust, interagency hazards information portal that provides relevant geospatial information to support response, recovery, and mitigation efforts. Information resources and interpretive products will support efforts to increase resilience and to ensure that decisions on coastal development and marine operations reflect changing exposure to natural hazards and attendant risks.

IMPROVING QUALITY OF LIFE

VISION

The uses and users of the nation's coasts are remarkably varied—from the intense, cosmopolitan settlements of New York City or Chicago, to the recreation and retirement-oriented areas of Cape Hatteras or the Florida Keys, to the low-settlement, petroleum- and fishing-centered Louisiana coasts, or to the Native subsistence settlements along much of the Alaska coasts. To improve quality of life[xxxvii], society must value and protect diverse, healthy ocean and coastal ecosystems and, at the same time, facilitate access to, enjoyment of, and sound (e.g., sustainable) use of these areas by the many and varied people who live, work, and play within these ecosystems.

RATIONALE

The concentration of our population in the coastal regions of the country is related to our nation's history, to the economic productivity of the regions, and, increasingly, to the quality of life in our coastal areas.

- Tourism is the world's largest industry and supports ten percent of all jobs[xxxviii].
- The U.S. cruise industry and its passengers spend $11 billion annually.
- The recreational saltwater fishing industry is valued at around $20 billion.
- Annual recreational boating expenditures are $30 billion[xxxix].
- Intensified coastal development continues to place more people and property at risk from weather-related hazards. In 1950, coastal population density was 42 per square kilometer (sq km); in 1994 it was 105 per sq km; and is projected to be 126 per sq km in 2015[xl].
- The coastal zone generates more than 56% of the nation's gross domestic product[xli].
- "Gentrification" of coastal communities is displacing many traditional coastal industries.

The factors that underlie quality of life are the main focus of the U.S. Ocean Action Plan: economic productivity, human and ecosystem health, recreation, pollution mitigation, marine debris cleanup, and conservation of resources. Concerns about these factors are rising as coastal populations grow and diversify and as we use the entire ocean more extensively.

CHALLENGES

The uses of the coasts and coastal waters—transportation, commercial fishing, agriculture, fabrication and manufacture, energy production, trade, beach and theme-park recreation, recreational fishing, boating, and swimming, retirement—all have different constituencies, resource requirements, and environmental consequences. The quality-of-life challenge for government at all levels is to manage these varied demands, expectations, and outcomes equitably and with the least possible negative impact to coastal and marine systems.

Research challenges associated with quality-of-life issues include the physical and environmental needs of ocean uses such as construction, recreation and tourism, their impacts, and the management of real and perceived conflicts among these contending uses. Examples are:

- Understanding the social/biogeochemical causes of water-quality degradation to prevent or mitigate impacts to sensitive ecosystems.
- Determining coastal erosion patterns for various coastal types and uses, as well as mitigation and replenishment[14] techniques.
- Evaluating ocean pollution, taking into account point and non-point sources, transportation regimes, and effects.
- Determining measures of impact for key use-types that take into account local and seasonal variability and consider conflicts between uses.
- Developing "smart climatology" that integrates long-range planning with predictions of season-to-interannual variability (such as summers with increased likelihood of hurricanes in the Southeast).
- Promoting "smart mapping" of coastal use that integrates information on environmental, demographic, and economic conditions and trends at local, regional, and state levels.

RESEARCH NEEDS

Understanding how to enhance the quality of life while protecting the resources that provide that quality represents a particularly complex challenge to scientists, managers, and planners. Several key types of research are required to do this. They fall into two distinct groups. The first includes expanding efforts to investigate, monitor, and forecast the direct impact of societal infrastructure and uses on coastal and ocean systems[16,30].

- Evaluate the effects of development (land-based development, land use, concurrent coastline modification, increased recreational use) by monitoring direct impacts (e.g., land erosion, sedimentation, pollution [point and non-point[63] input], ecosystem degradation[19]) and indirect impacts (e.g., higher traffic due to improved water access).
- Assimilate monitoring data into coastal ecosystem models to predict short-term (days to months) and long-term (months to years) cumulative impacts of current and future coastal and watershed development and uses.

The second group includes efforts to examine the socio-economic impact of the multiple, often conflicting, uses of the ocean and investigate cultural acceptance of changing uses.

- Examine the effects of climate change (e.g., rising sea level, changing lake levels) on coastline and societal development[46] and incorporate results into land-use models for improved prediction of environmental impacts.
- Investigate socio-economic effects of alterations in ecosystems on resource users (e.g., development of marine reserves[53], resource extraction[25], displacement of fishing communities due to fisheries collapse).

- Conduct detailed observational and questionnaire-based studies of user groups and resource needs and incorporate results into local, state, and federal planning and management initiatives (e.g., Coastal Zone Management [CZM]).

INFRASTRUCTURAL AND TECHNOLOGICAL NEEDS

Several key technological and infrastructure investments will support efforts to understand the impact of often-conflicting uses of oceanic resources. These investments include local and global observations, information sharing among scientists, planners and users, and integration of data into coastline planning. Investments should include:

- Development of a computer-based geographic information system (GIS) that integrates diverse social, economic, geographic, and environmental data, along with an information portal for integrated data dissemination.
- Integration of regional and state agency research products with data from global observatory, and modeling and data synthesis programs to understand the local impacts[3] of world-wide phenomena (e.g., rising sea level due to climate change).
- Integration of regional observatory data[xlii] and model results with state, regional, and federal planning data systems and models.
- Development and enhancement of observatory-based educational tools for multiple user groups.

EXPECTED RESULTS

The integration of environmental observations and modeling with socio-economic assessments of multiple user groups will produce an information system capable of developing useful products to significantly advancing coastal planning and decision-making. This integrated information system will allow federal, state, and local governments to:

- Understand the demands on coastal areas by various uses (e.g., urbanization, agricultural development, recreation) and the consequences of these uses (e.g., sediment or nutrient inputs, marine debris, coastal access), thus balancing more effectively the uses of coastal and marine environments and cumulative impacts on them.
- More effectively mitigate the adverse consequences (e.g., through the development of advanced information systems the advancement of environmentally friendly developmental practices [e.g., runoff mitigation], improved public awareness), thus helping to reduce the loss of lives, jobs, and destruction of ecosystems.
- Better plan for and coordinate among the contending and conflicting uses of the coasts by coastal management procedures.

ENHANCING OUR BASIC UNDERSTANDING OF THE OCEAN

Society's best opportunity to create and maintain economic and social wealth from the ocean, yet sustain its bounty for the future generations, comes from developing the best and most complete understanding of how the ocean functions and responds to perturbations. Previous themes have focused on solving specific problems of great importance to society. We must formulate our approaches to answering scientific questions about these problems based on our current understanding of the ocean. But if our understanding is incomplete or flawed because we are unaware of important processes or relationships, we may design the wrong sampling program, measure the wrong parameters, or draw the wrong conclusions. It is for this reason that it is essential that we continue to explore new ideas about the ocean and develop new approaches for exploring the ocean that may not be directly related to specific products or societal requirements or that may challenge existing ideas about the ocean. Experience has certainly shown that benefits in the form of new products and services often result from unexpected discoveries. Equally interesting, some ocean study leads to deeper understanding of our relationship to the oceans and to understanding the long-term history of Earth and its ocean. Our strategy must include "room for creative individuals to pursue the kind of fundamental scientific research that can led to unforeseen breakthroughs."[xliii]

Understanding the ocean environment and its role in the Earth system (including the atmosphere, cryosphere, biosphere) requires answering very challenging questions:

- What are the natural processes that govern variability and change in the ocean?
- How do the ocean, coasts and Great Lakes respond to—and contribute to—natural and human-induced changes?
- What are the primary causes of change in the ocean and how will the ocean's systems respond?
- In what ways is the ocean linked to the Earth system?

Marine ecosystem dynamics, the physical complexity of the ocean environment, and biogeochemical processes occurring at boundaries are key to understanding living marine resources. Oceanic fluxes of heat, water, momentum, and biogeochemical properties are essential to understanding the oceans and the carbon cycle. Ocean circulation, ocean turbulence, and air-sea interactions study is needed to understand how the ocean will respond to climate change. Study of the processes occurring at coastal margins, including estuarine and watershed systems, is necessary to understand how to preserve the quality of life in our coastal environments.

EXPLORATION

Exploration is an important process in expanding our understanding. We generally think of exploration in terms of visiting geographic areas that have not been studied extensively in the past. But exploration can include study of different spatial scales. For example, new technological advances in nanoscale science hold promise of unlocking our understanding of fundamental ocean processes at their atomic and molecular level. At the opposite end of the spatial spectrum, measurements from remote-sensing platforms, including satellites and aircraft, are needed to enhance *in situ* data and provide a more comprehensive view of global and regional changes in the ocean environment, particularly in areas where *in situ* data are limited or unavailable.

Exploration can also focus on different temporal scales. Sustained time-series observations (including the ability to observe on extremely short and long time scales) are essential for understanding temporal trends in the ocean[31,82]. For example, repeat measurements of physical processes over several decades in the Atlantic Ocean revealed a decade scale variation in North Atlantic circulation, the North Atlantic Oscillation, which has explained various relationships that had perplexed oceanographers.

Many of the questions posed in the specific themes cut across traditional disciplinary boundaries. What new insights about the ocean will come from engineering and social science research?

NEW TOOLS

Continued innovation is needed to develop research tools. A suite of tools -- from remotely operated and autonomous vehicles41, to acoustic and visual imaging and mapping systems, to physical, chemical, and biological sensors is needed to facilitate novel experiments and to measure processes from short-lived episodes to global cycles. Some tools are physical instruments, but others are new methods. For example, study of the distribution of specific isotopes often allows them to be used as proxies for complex ocean processes than cannot be measured directly. Molecular and genomic methods promise to revolutionize our understanding of biological processes in the ocean.

OBSERVATIONS/INFRASTRUCTURE

RATIONALE

The ocean is a cold, dark, high pressure, and corrosive environment, hard on humans and their machines. As such, it remains the least explored and most under-sampled environment on Earth. Observations are needed for a wide range of physical, biological, chemical, geological and atmospheric variables within U.S. coastal regions, islands and territories, and open ocean regions. Coordination of this information obtained at various time and space scales, and from existing and planned networks, along with indicators, models and decision support systems can provide great benefits to society.

In addition, the field of oceanography is evolving rapidly—transitioning from widely separated individuals making non-standardized measurements for their own purposes to automatic reporting networks making robust standardized measurements for multiple purposes (much like that of meteorology). Similarly, ocean data assimilation and modeling capabilities will soon have the capacity to incorporate global and local observing data to produce robust, high-resolution simulations.

OBSERVING SYSTEMS

In recent years, there has been a growing recognition of the need to better integrate and utilize Earth observations in general, as exemplified in the intergovernmental Global Earth Observations System of Systems (GEOSS). The U.S. contribution to GEOSS, the Integrated Earth Observing System includes "Protect and Monitor our Ocean Resources" as one of the nine societal benefit areas.[xliv]

Much of the infrastructure called for within each of the themes discussed in this document has been proposed as part of the Integrated Ocean Observing System (IOOS), in the First U.S. Integrated Ocean Observing System (IOOS) Development Plan,[xlv], which describes an "end-to-end," user-driven system of observations, and data management, communications, and analysis (with the associated governance), designed to address the over-arching themes within this planning document. IOOS is the United States' contribution to the Global Ocean Observing System (GOOS), which, in turn, is the ocean contribution to GEOSS. The IOOS is comprised of two interdependent and nested components—one for the nation's coastal systems (ranging from our shorelines out to the edge of the EEZ and the Great Lakes), and one for the global ocean. The coastal component is designed to detect, assess, and predict the effects of weather, climate, and human activities on the state of the coastal ocean, its ecosystems and living resources, and the U.S. economy. It consists of a national backbone of existing observing systems, such as National Data Buoy Center (NDBC) platforms, and regional coastal ocean observing systems (RCOOSs)[38] that are coordinated by Regional Associations (RAs). These regional systems are designed to address region-specific observing requirements by increasing the number of parameters measured, allowing higher data sampling rates, and covering a broader area. The global ocean component is being implemented with international partners to improve forecasts and assessments of weather, climate, and ocean states, as well as to provide boundary conditions for the coastal component.[39] The global system is comprised of complementary *in situ* (ships, buoys, floats/drifters, fixed platforms) and space-based observing systems (e.g., satellites).

Although the IOOS will have a research and development element, a future basic research component of the IOOS will be the Ocean Observatories Initiative (OOI). The OOI will provide the U.S. ocean sciences research community with access to basic infrastructure required to make sustained, long-term, and adaptive measurements in the ocean and on the seafloor. Similar to the IOOS, the OOI has global, regional, and coastal components[xl]. The technological foundation of the regional OOI—a fiber-optic cable that transmits data to shore in real time—is based on several successful pilot and test-bed projects. As these research efforts mature, the coastal, regional, and global observatories enabled by the OOI will increasingly become an integral part of the IOOS. The continuing technological innovation enabled by the OOI will serve evolving research needs and help transition advanced technologies from research to operations.

NEW AND EXISTING PLATFORMS

Innovation in ocean research will be fostered through increased access to the ocean, coasts, and Great Lakes and by addressing the technological challenges associated with providing this increased access. In addition to platforms that enable expanded temporal and spatial access to the ocean, such as global, national, and regional observing systems and a robust research fleet (that includes manned submersibles[41]), land-based marine laboratories are required to enable multidisciplinary research programs and to support specialized equipment and instrumentation.

DATA AND MODEL DEVELOPMENTS

The ocean observation systems that are now possible require innovations in the ways in which data are collected, archived, made available, analyzed and assimilated into models. Questions about how the ocean will react to conditions in the future or about the oceans of the past cannot be answered by observation. They can only be explored through the combination of theory and modeling. Modeling is fundamental to each of the themes in this report. The capability to reliably predict phenomena ranging from global sea-level rise to coastal and estuarine hypoxic events will have profound implications for society now and in the future. A suite of modeling capabilities is currently in use, with a spectrum of scales (0.01 m to 40 km) and periods (1 hr to 100 yrs). Some are sufficient for the processes that are to be predicted, others require advances in understanding. Community models, reflecting shared development, regular user interaction, and ready availability of software and documentation, are also emerging in some areas of ocean science research[xlvi]. Future modeling efforts may include a high-resolution national model of the global ocean, with wide ranging forecasting capabilities (days to centuries), capable of integrating with even higher-resolution regional modeling efforts

Both large-scale ocean observation and ocean simulation require enhanced computational capabilities. And all of these challenges require development of adequate cyberinfrastructure—middleware, software, networking tools, collaboratory software.

OBSERVATIONS/TECHNOLOGY NEEDS

Additional developmental and integration steps are required to take full advantage of the capabilities of the fleet, and observing, computational, and modeling assets:

- fully integrating elements of the "National Backbone" of IOOS;
- improving biogeochemical measurements;
- deploying enhanced sensor packages that are more precise and accurate, are automated, and require less maintenance;
- improved remote sensing measurements (e.g., calibrating and representing data in coastal water; precise sea surface height and surface vector wind measurements; and integration of *in situ* measurements with remotely-sensed observations);
- expanded ship-based measurements, such as increased use of ships of opportunity, comprehensive and standardized fisheries and protected species surveys; and multi-beam sonar measurements;
- expanding availability of, and access to, standardized ocean modeling software and necessary computational resources;
- advancing necessary aspects of observing data management, including data assimilation, distribution, and archiving;
- integrating observational and modeling efforts and individuals to effectively use the output of the observing systems and develop high-fidelity ocean models; and
- optimizing research and development efforts of observing systems to promote the evolution of these systems in addressing future research and user goals.

EXPECTED RESULTS

The wealth of information collected by next-generation technology and analyzed by scientists using the most advanced computers will provide the foundation for profound advances in scientific understanding of the Earth system, and will serve the needs for ocean resource managers.

OCEAN EDUCATION

RATIONALE

The value of the ocean as an integral part of the Earth system must be understood by society to ensure governance that uses ocean sciences research in effective decision-making and science education reform, and to build and sustain a qualified and competitive workforce prepared with scientific understanding of the ocean. Our goal is a nation whose citizens are good stewards of the ocean and respond appropriately to information relayed about it. This goal can only be attained through improved education efforts—encompassing ocean literacy for the general public, formal and informal education, proactive workforce development, and effective communications.

The diversity of research activities as exemplified in the Ocean Research Priorities Plan, demonstrates the rich potential for multiple educational opportunities that would support and benefit from our nation's oceanographic research enterprise.

EDUCATION NEEDS IN SUPPORT OF OCEAN RESEARCH

FORMAL AND INFORMAL EDUCATION

Interest and involvement with the ocean and our interaction with it depends on exposure to its intricacies and many mysteries. The scientific initiative and curiosity that will generate future innovations and discoveries will come only with the expansion of oceanographic knowledge for all citizens. Currently, ocean studies are not part of the formal K–12 curricula in most areas of the country, and ocean science concepts are missing from most standards and assessments. At the secondary and undergraduate levels, some earth science courses are severely lacking in ocean science content. Recent efforts have focused on establishing the strong linkage between the fundaments of ocean literacy and established national science education standards (one project has completed a definition of ocean literacy in the context of science and has mapped ocean content to the National Science Education Standards.)[xlvii]

Aquaria, museums, science centers, zoos, and other informal education centers welcome over 35 million visitors a year and play a major role in educating the public about the ocean. These forums for informal delivery of education are important conduits for the transfer of understanding about the ocean from the research community to the general public.

Inclusion of ocean sciences in curriculum at K–undergraduate levels of formal education, providing professional development opportunities for teachers and expanding informal education for the general public, are key steps in enhancing public knowledge of the ocean. Incorporation of educational goals will add value to research efforts. For example, the integration of ocean-observing data into K–12 classrooms and informal programs will help realize the full potential of the observing systems[89,90,91] and provide real-world application to the learning environment.

WORKFORCE DEVELOPMENT

The continued development of an innovative, inquisitive, ocean-science workforce dedicated to addressing the many research needs outlined in the developing Plan is essential to its success. The diversity of research requirements necessitates a workforce with interdisciplinary knowledge bases, the ability to develop and use key research tools, such as models, and the capacity to translate research results into tools for decision support. Additionally, as ocean observing systems are developed and integrated into scientific and public venues, the development of more technical and professional education programs is required to train the workforce needed to operate the systems. This effort will include providing diverse and innovative ocean-related education programs at the undergraduate, graduate, and post-doctoral levels and professional certification programs aimed at training an operational workforce for ocean-related jobs. Integral to this workforce expansion is the need to address profound demographic shifts toward under-represented segments of the population in the United States and, as a result, develop, implement, and sustain effective strategies for recruiting and retaining students from all population segments. Similarly, we should educate and train scientists from diverse cultural and occupational backgrounds in order to better utilize traditional ecological knowledge and experiences.

EDUCATIONAL ASSESSMENTS

Effective ocean education requires determining which educational practices are most effective for different audiences. Baseline assessments of ocean education will allow educators to determine the current:

- ocean workforce education capabilities and requirements
- level of public literacy on ocean-related issues
- ocean-related topics covered in each state's K–12 science standards and testing

This baseline information will also enable the measurement of progress toward improving ocean education. A "gap analysis" will determine what programs are being supported, if needed programs are not available, and how to coordinate efforts to support these programs. An integrated communication plan about ocean-related topics will increase the public's awareness and understanding of the complex issues surrounding the stewardship of the nation's waters and, by extension, the global ocean.

EXPECTED RESULTS

Educational efforts, ranging from workforce expansion to enhanced ocean literacy of the general public, will serve to advance not only the research efforts outlined in this Plan, but also the general stewardship of our ocean. These efforts will help to ensure the sustainable interaction of society with the ocean and its many resources, and will be reflected in marine and Great Lakes environments that are cleaner and healthier.

1
ENDNOTES

[i] The term “ocean” throughout this document is meant to include a broad set of environments, including open ocean, coasts and estuaries, Great Lakes and coastal watersheds.
[ii] http://www.oceancommission.gov/documents/full_color_rpt/000_ocean_full_report.pdf, p. 376
[iii] Oceans Act of 2000 (http://www.oceancommission.gov/documents/oceanact.pdf)
[iv] U.S. Ocean Action Plan, 2005, p. 3.
[v] http://ocean.ceq.gov/about/docs/JSOST_Priorities_040505.pdf
[vi] The deaths are nearly all from the species of naturally occurring marine bacteria, *Vibrio vulnificus*.
[vii] According to Kuiken et al. (Science 309:1680-1681, 2005), “Animals, particularly wild animals, are thought to be the source of more than 70% of all emerging infections…”Taylor et al. (Philos. Trans. R. Soc. London Ser. B 356: 983, 2001). Therefore, surveillance in animals for zoonotic pathogens-pathogens of nonhuman vertebrate animals that may be transmitted to humans under natural conditions-is critical for managing these infections.”
[viii] U.S. Ocean Commission, p.315
[ix] “Seafood” refers to salt, brackish, and Great Lakes food sources.
[x] Excluding allergic reactions to seafood
[xi] U.S. Ocean Commission, Final Report, pp. 340–342.
[xii] Kleeman, E. 2005. Biologists find life in dark rigid trough. *Discover* 26(11)
[xiii] NOAA Technical Memorandum NOS NCCOS 11.
[xiv] U.S. Commission on Ocean Policy, Final Report, p. 2
[xv] Minerals Management Service
[xvi] U.S. Commission on Ocean Policy, Final Report, p. 275.
[xvii] NOAA Fisheries Data Acquisition Plan, 1998.
[xviii] U.S. Commission on Ocean Policy, Final Report.
[xix] Marine Operations includes international and national coastal and ocean transportation, marine commercial operations at sea, and ocean-related homeland and national security concerns. It encompasses international issues including freedom of navigation in the global commons, U.S. coastal issues including mapping and charting, and activities in U.S. ports, harbors, and estuaries and the Great Lakes, including dredging, navigation aids, and ice. Not explicitly included are issues of living and non-living resources, human and ecosystems health concerns, or natural hazards even though the interactions with these topics are substantial.
[xx] U.S. Commission on Ocean Policy, Final Report, p. 193.
[xxi] U.S. Commission on Ocean Policy, Final Report, p. 192.
[xxii] U.S. Commission on Ocean Policy, Final Report, p. 194
[xxiii] U.S. Commission on Ocean Policy, Final Report, p. 200.
[xxiv] U.S. Customs and Border Protection
[xxv] http://www.nap.edu/execsumm/0309088607.html
[xxvi] http://www.fas.org/man/dod-101/sys/ship/intro.htm
[xxvii] http://neds.daps.dla.mil/5090.htm
[xxviii] www.ndia.org/Content/ContentGroups/ Divisions1/International/MDA_USCG.ppt
[xxix] Research efforts for marine transportation will be coordinated with efforts of the cabinet-level Committee on the Marine Transportation System (CMTS) (www.waterways-rd.gov/about/CMTS.htm).
[xxx] http://www.climatescience.gov/Library/stratplan2003/final/default.htm
[xxxi] http://www.ncdc.noaa.gov/oa/reports/tech-report-200501z.pdf

[xxxii] NSTC, Subcommittee on Disaster Reduction, *Grand Challenges for Disaster Reduction,* p. 8.
[xxxiii] NSTC, Subcommittee on Disaster Reduction, *Grand Challenges for Disaster Reduction,* p. 6.
[xxxiv] http://www.ngdc.noaa.gov/seg/hazard/tsevsrch_idb.shtml
[xxxv] NSTC, Subcommittee on Disaster Reduction, *Grand Challenges for Disaster Reduction,* p. 1.
[xxxvi] Decision support tools such as a National Coastal Community Resilience Index will enable decision-makers to define and quantify potential hazard impacts.
[xxxvii] Quality of life is generally defined as the health and social well-being of people. The topic as discussed here focuses on social well-being and includes preservation (such as pollution prevention and shoreline protection), improvement, (such as pollution prevention and remediation) and stewardship (such as facilitating multiple uses and access). (Oceans 2000: Bridging the Millennia; Partnerships for Stakeholders in the Oceans.)
[xxxviii] Project AWARE: http://www.projectaware.org
[xxxix] U.S. Commission on Ocean Policy: http://oceancommission.gov/documents/full_color_rpt/welcome.html
[xl] The Heinz Center. 2002. *Human Links to Coastal Disasters.* The Center for Science, Economics and Environment. Washington, D.C.
[xli] www.noep.csumb.edu
[xlii] http://usnfra.org/
[xliii] US Commission on Ocean Policy, Final Report, p. 327.
[xliv] Strategic Plan for the U.S. Integrated Earth Observing System
[xlv] (http://www.ocean.us/documents/docs/IOOSDevPlan_low-res.pdf)
[xlvi] OITI Steering Committee. 2002. An Information Technology Infrastructure Plan to Advance Ocean Sciences, 80 pp., http://www.geo-prose.com/oiti/report.html
[xlvii] http://www.coexploration.org/oceanliteracy/)

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3 *A Climate Services Vision: First Steps Toward the Future.* 2001. Available at: http://books.nap.edu/catalog/10198.html

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9 *America's Lab Report: Investigations in High School Science*. 2005. Available at: http://books.nap.edu/catalog/11311.html

10 *Assessment of Department of Defense Basic Research.* 2005. Available at: http://books.nap.edu/catalog/11177.html

11 *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities, Interim Report.* 2004. Available at: http://books.nap.edu/catalog/11195.html

12 *Atlantic Salmon in Maine*. 2004. Available at: http://books.nap.edu/catalog/10892.html

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